HIGH EFFICIENCY CONVERTERS FOR SMALL RADIOISOTOPE POWER SOURCES

Mark L. Underwood and Richard C. Ewell
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109-8099
(818) 3s4-9049

ABSTRACT

Outer planet rendezvous and planetary surface exploration missions are often most logically powered by thermal-to-electric converters with heat supplied from a radioisotope heat source. A new generation of converters is near technology readiness and soon should be available to provide spacecraft power. These converters promise up to four fold improvements in power density (W_e/kg) and a 60% or greater reduction in radioisotope requirement as compared to current radioisotope thermoelectric generator (RTG) technology. As part of the 1993 Pluto Advanced Technology Insertion program, high efficiency converters were examined with the goal of reducing the power source mass and heat source inventory. Two technologies, the Alkali Metal Thermal-to-Electric Converter (AMTEC) and Thermophotovoltaic (TPV) converters, were examined through short term, hardware focused programs. A small Stirling Engine design was also completed specifically for the Pluto mission. Projected power system performance, technology development status, and estimated cost and schedule to completion of development will be reviewed. For comparison to the advanced technologies, the Pluto Fast Fl yby Pre-project 1993 baseline power source is a small RTG. This RTG is a scaled down GPHS RTG with an inventory of 5 General Purpose Heat Sources (GPHS), a mass of 15.4 kg, and an output of 70 W_e after 9 years.

AMTEC research was carried out by the Environmental Research Institute of Michigan (ERIM). Four, near-prototypic AMTEC cells were fabricated and tested with each cell including evolutionaril y improved components and performance. The second of the four cells operated at 10% conversion efficiency at 700°C. The fourth cell operated at an estimated 10% efficiency at 650°C before an external hardware failure forced the end of the test. The cell was projected to reach 16% efficiency at 750°C. These are the highest efficiencies yet demonstrated with compact AMTEC cells. Further improvements in the design are projected that would to lead to an AMTEC system for the Pluto mission with a reduction of 37% in mass and 60% in heat source inventory compared to the RTG baseline.

TPV converter experimental research was conducted by the Boeing Defense and Space Group. A one third scale TPV system was fabricated and tested. This was the first demonstration of an entire TPV system (exclusive of the radiator) designed for the temperature range achievable by the GPHS. The system was composed of a GPHS simulating heater, a thermo-optical cavity, and two arrays of TPV cells and filters. Up to 13% of the thermal input to individual filter/cell assemblies was converted to electricity. The "photon recycling" performance of the optical cavity was not as good as expected resulting in low system performance. Based on the demonstrated performance of the Boeing TPV cells and filters, JPL designed a TPV system that could meet the needs of the Pluto mission with a reduction of 28% in mass and 40% in heat source inventory compared to the RTG baseline. With some performance enhancements now being investigated, these values could be reduced further.

Stirling converter design was done by NASA Lewis Research Center and is based on their extensive experience with design and testing of Stirling engines. The design uses dual, opposed Stirling engines to minimize potential spacecraft vibration and to provide full power in the event that one engine fails. The Stirling system could provide the Pluto mission with a reduction of 17% in mass and 60% in heat source inventory compared to the RTG baseline. This design indicates that Stirling engines are competitive on a mass basis with advanced static conversion technologies at low power levels.

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By: Dr. Mark L. Underwood and Richard C. Ewell
Jet propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

Ph# (818) 354-9049
fax#(818) 393-4272

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Pluto Advanced Technology Insertion

- **Pluto ATI Goals**
  - Incorporation of New Technology in the Spacecraft Design
  - Spacecraft Mass Reduction
    - » The RTG was the most massive item on the FY92 spacecraft.
  - Mission Cost Reduction
- **Pluto ATI Power Conversion Technologies**
  - AMTEC – Alkali Metal Thermal-to-Electric Converter
  - TPV – Thermophotovoltaic Converter
  - Stirling Engine Isotope Power System
- **These New Technologies have the Potential to:**
  - Reduce power source mass by 50%or more
  - Reduce radioisotope inventory by 60% (5 GPHS modules to 2)

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Key ATI Results

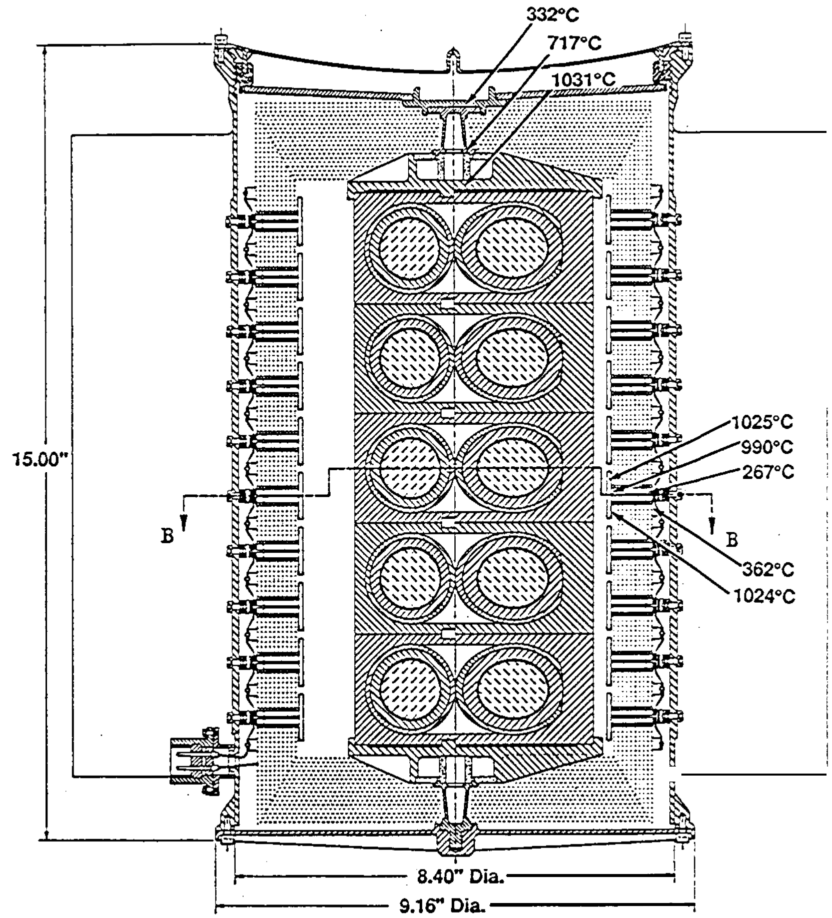
- **AMTEC**
  - First demonstration of near-prototypic space AMTEC cells
  - 10% cell efficiency demonstrated with development path to system efficiencies of 18% or higher
- **TPV**
  - First demonstration of all TPV system functions (except radiator) in the temperature range for radioisotope systems
  - Demonstrated Cell/Filter efficiency of 13.3%
- **Stirling**
  - Demonstrated competitiveness of Stirling power systems on a mass basis even down to power levels less than 100 W_e
  - First system design and analysis of a GPHS-heated Stirling power system for less than 100 W_e

Pluto Power Source Outlook

- The Pluto ATI Demonstrated that:
  - High efficiency thermal power conversion technologies are available
  - All three technologies could significantly reduce the power source mass and radioisotope inventory
- No advanced technology can be expected to be ready for launch on a near-term Pluto mission
  - Funding limitations
  - Development risk
  - RTG Power Source retained as the baseline
- Pluto ATI has significantly advanced these technologies for future applications

P uto Base ine RTG

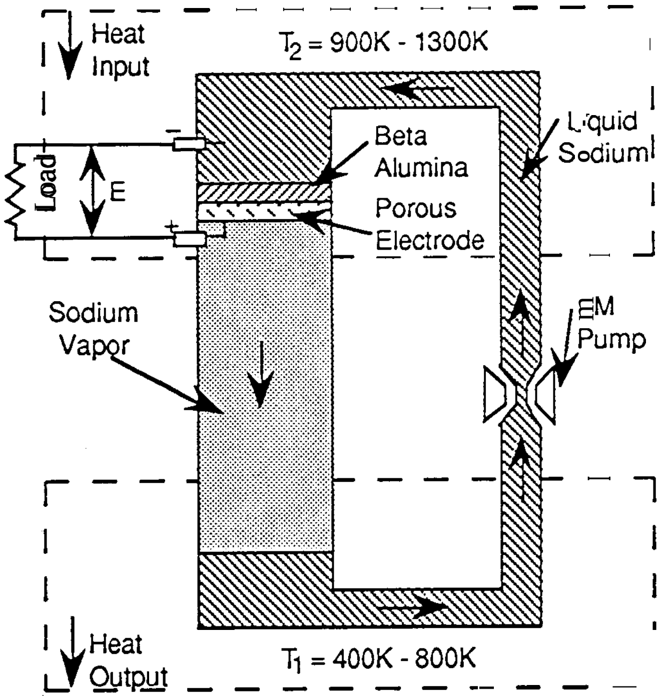
- **Performance Parameters:**
  - Mass: 15.4 kg
  - # GPHS: 5 (each 250 W_t BOM)
  - Power Output: 85 W_e (BOM)
  - Innovations: Low Mass Supports



»For more details see:
Alfred Schock, "Radioisotope Thermoelectric Generator Options for Pluto FastFlyby," Fairchild Space and Defense Corporation, Germantown, MD

AMTEC Description

- **The Alkali Metal Thermal-to-Electric Converter**
  - A thermally regenerated, electrochemical concentration cel



- **Advantages**
  - Static System
  - High Efficiency & Power Density
  - Modular
  - Uses Commercially Available Materials

»For more details see:

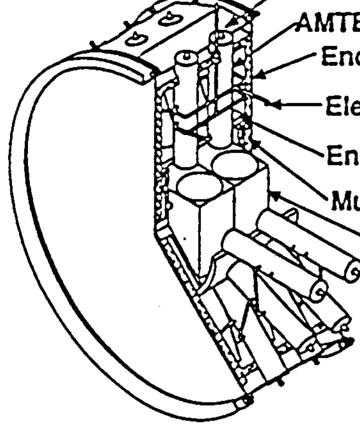
Weber, N. (1974) "A Thermoelectric Device Based on Beta Alumina Solid Electrolyte," Energy Conversion, 14, pp. 1-8.
Cole, T. (1983) "Thermoelectric Energy Conversion with Solid Electrolytes," Science, 221, pp. 915-920.

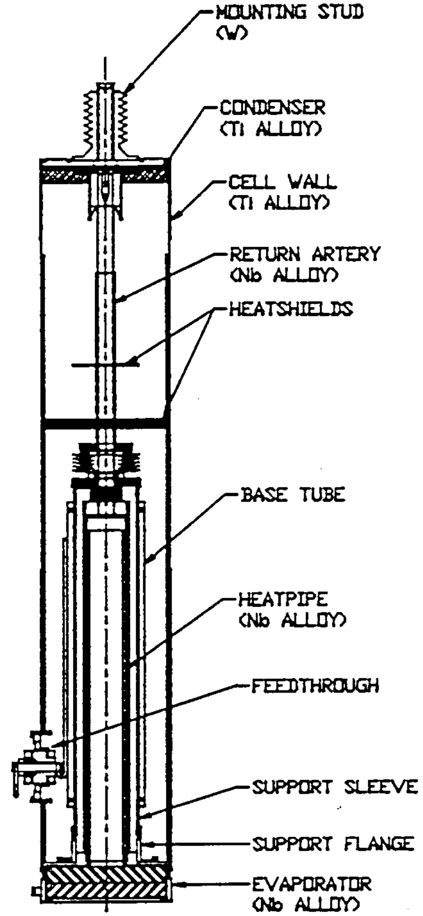
AMTEC Systems Design

◆ Performance Parameters:

- Mass: 9.8 kg
- # GPHS: 2
- Power Output: 76 W_e (BOM)

»For more details see:
J.F. Ivanenok III, et. al. "Radioisotope AMTEC Power System Designs for Spacecraft Applications," in Proceedings of the 28th IECEC (1993), American Chemical Society, Vol 1, p 655.

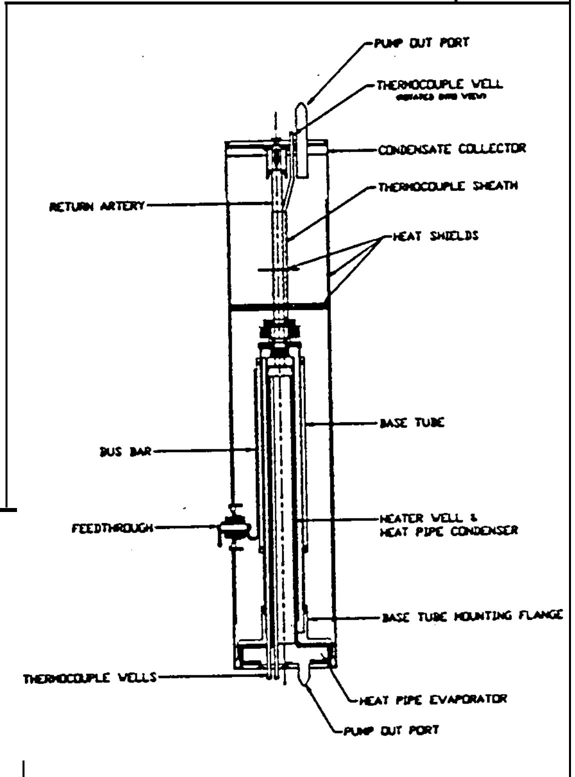


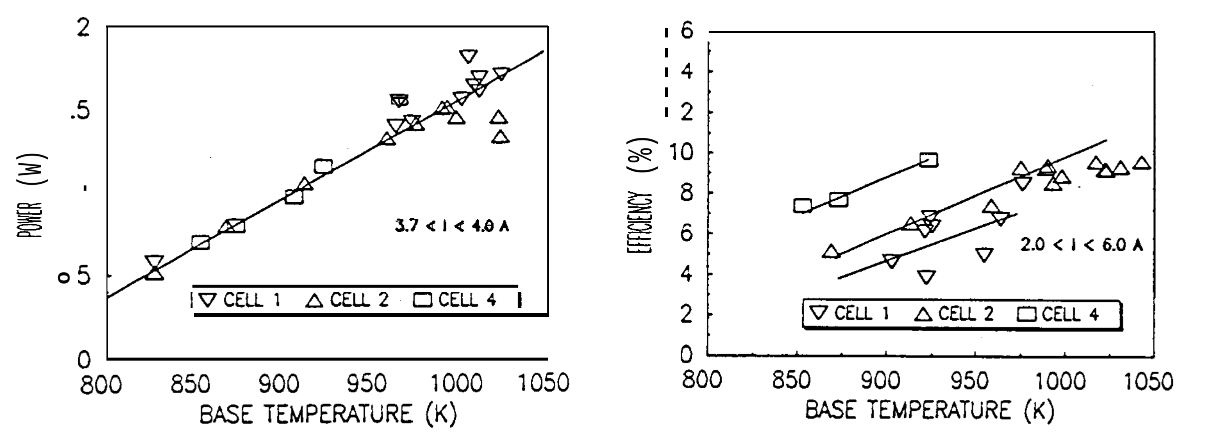


»AMTEC ATI research was performed by the Environmental Research Institute of Michigan (ERIM) under contract to JPL.

AMTEC Experimental Results

- ◆ **Efficiency Demonstration**
  - – 10% measured, 14% projected
- ◆ **Power Demonstration**
  - – Power output up to 1.6 W_e/cell
- ◆ **Mechanical Durability Demonstration**
  - – Durability to shock and vibration loads





»For more details see:
R.K. Sievers, et. al., "Designa and Testing of AMTEC Mini-Cells," in Proceedings of the 11th Space Nuclear Power Symposium (1994), American Institute of Physics.

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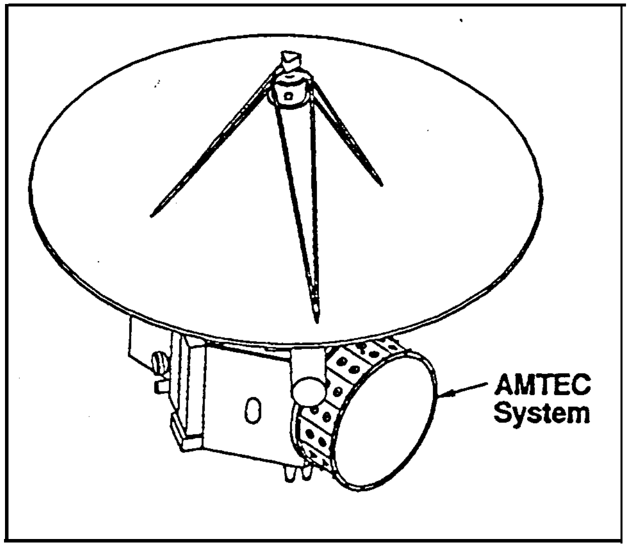
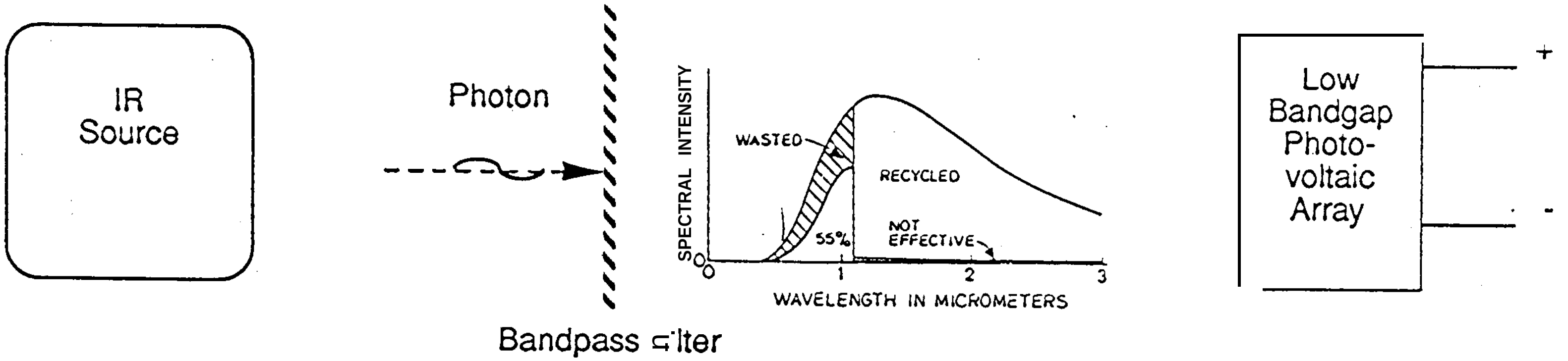
AMTEC Prospects

- **Development Continues**
  - At ERIM Pluto-like cells have recently demonstrated 15% conversion efficiency and further improvements are projected
  - Space Solar designs are being investigated
  - ERIM is also planning terrestrial uses for AMTEC
  - Fundamental understanding is being completed at JPL
- **Flight test Planned**
  - Selected for In-STEP Flight Experiment (Joint JPL & ERIM)
  - Phase A begins in 1994, Flight expected before ≈997
- **Remaining Issues**
  - Performance in Zero-Gravity
  - Lifetime



TPV Description

- **Thermophotovoltaic Converter**
  - Capture of infrared radiation by a low bandgap photovoltaic
- **Advantages**
  - Static System
  - High Efficiency & Power Density with "Photon Recycling"
  - Photovoltaics developed under a separate program

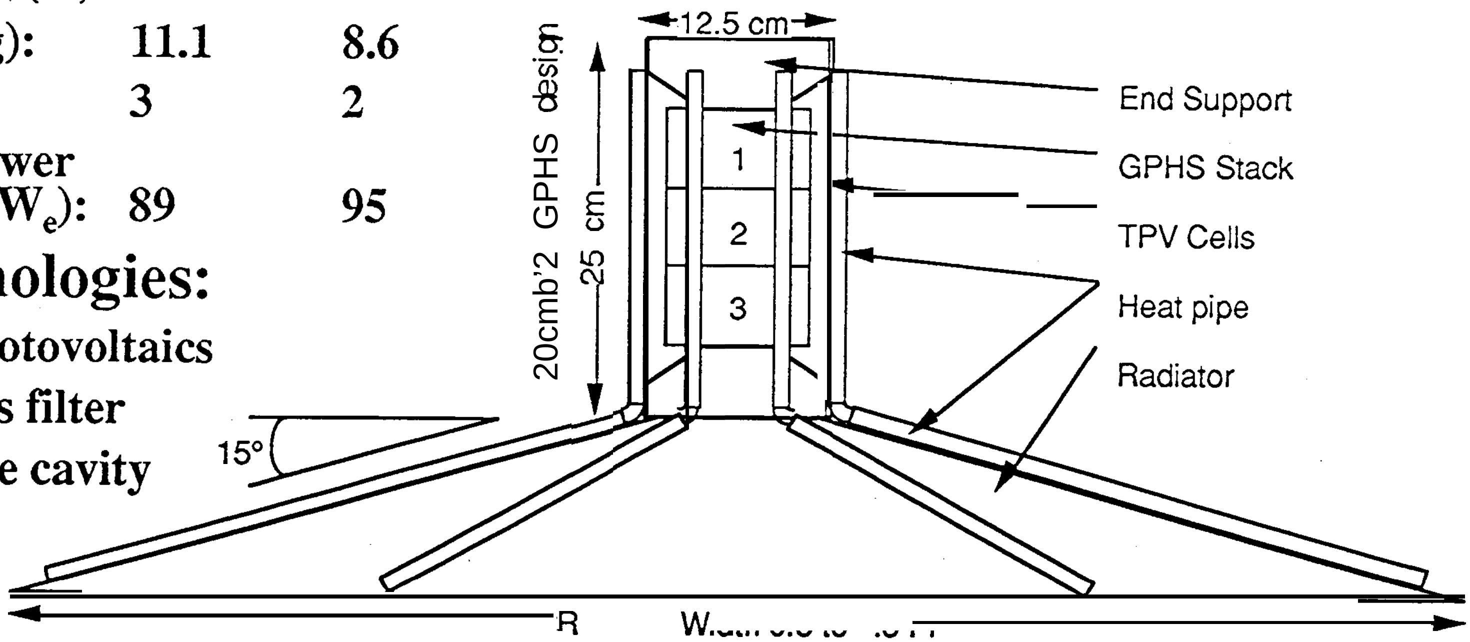


»For more details see:
A.C. Day, W.E. Horne, and M.D. Morgan, "Application of the GaSb Solar Cell in Isotope-Heated Power Systems," Proceedings of the 1990 IEEE photovoltaics Specialist Conference, 1990.

TPV Systems Design

- **Performance Parameters:**
  - Technology: Current Advanced
  - Radiator Diameter (m): 1.0-1.3 0.8-0.9
  - Mass (kg): 11.1 8.6
  - # GPHS: 3 2
  - BOM Power Output (W_e): 89 95
- **Key technologies:**
  - GaSb photovoltaics
  - Bandpass filter
  - Reflective cavity

JPL TPV System Concept



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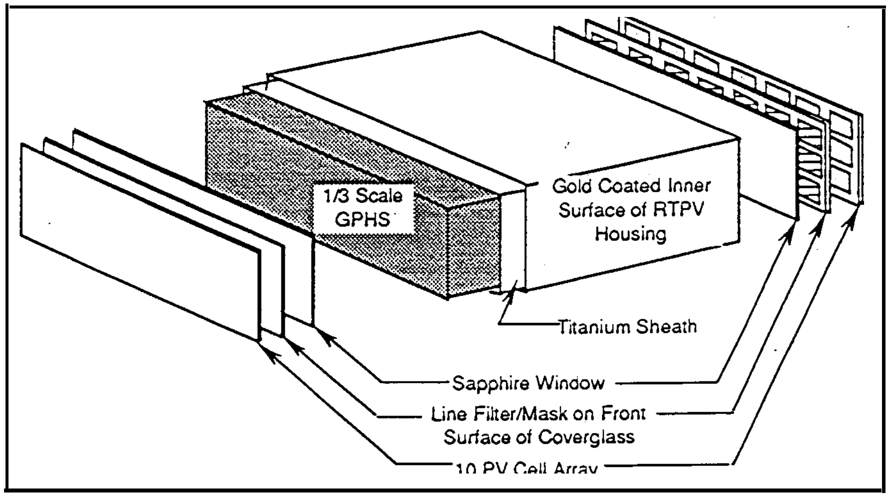
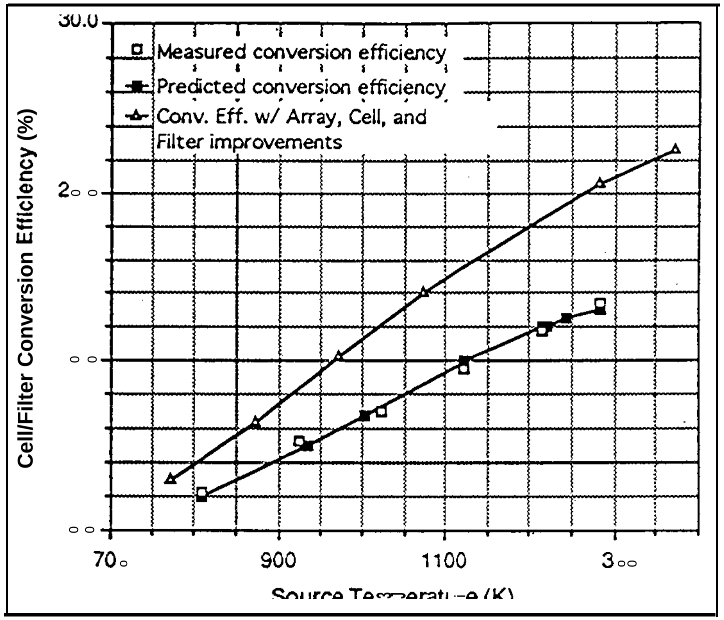
TPV Experimental Resul s

- **Filter Fabrication**
  - Up to 65% transmission at peak wavelength
- **System Demonstration**
  - Up to 13.3 % filter/cell efficiency was measured
  - Very close match of experiment and model





»TPV ATI experimental work performed by the Boeing Defense and Space under contract to JPL

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TPV Prospects

◆ Development Continues

- Fairchild Space and Defense competed a TPV system concept predicting a 2 GPHS, 7.2 kg design producing 76 W_e (BOM, near term technology) to 134 W_e (BOM, predicted improved technology)
    - » Reference: A. Schock et. al. "Radioisotope Thermophotovoltaic (RTPV) Generator and Its Applicability to an Illustrative Space Mission," Fairchild Space and Defense Corp., Germantown MD, FSC-ESD-93-519A.
- DOE has issues an STTR solicitation for TPV development
- TPV also has terrestrial uses that are being developed

◆ Remaining Issues

- Filter optimization and performance and/or emitted spectrum modification
- Radiation degradation of photovoltaics (some data exists for GaSb)
- Lifetime, including life limiting mechanisms and contamination of reflective surfaces
- System efficiency demonstration

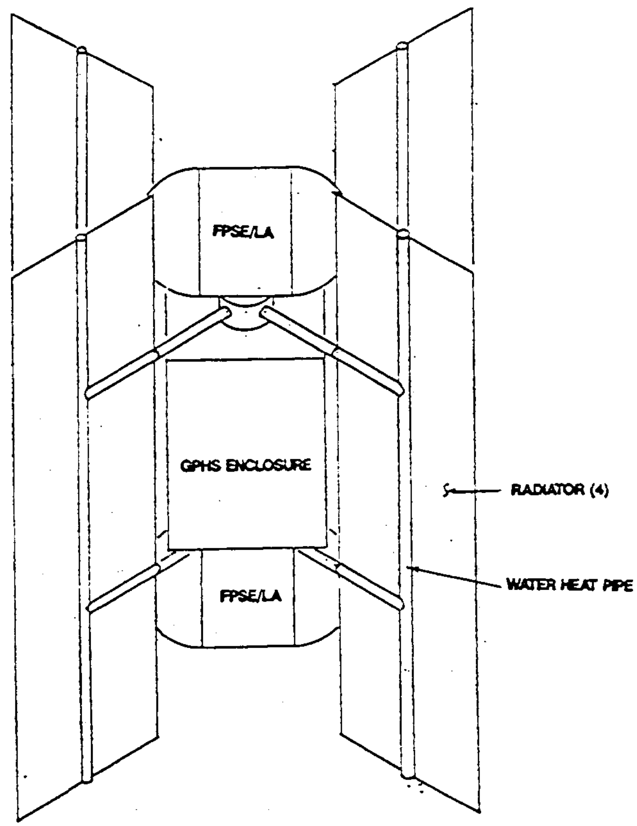
Stirling Engine Description

- Stirling Engine Isotope Power System
  - Free Piston Stirling Engine combined with a Linear Alternator
  - Mechanically Simple, 2 moving parts per engine
  - Hermetically sealed
  - Pistons suspended on linear gas bearings or flexures
- Advantages
  - Similar to Stirling Cryocoolers that have operated in space
  - Scalable to a wide range of power levels
  - Single frequency vibration easily attenuated

»For more details see:
D.J. Bents, et. al. "Design of Small Stirling Dynamic Isotope Power System for Robotic Space Missions," in Proceedings of the Tenth Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM Jan. 1992.

Stirling Engine Systems Design

- **Performance Parameters:**
  - Mass: 12.75 kg
  - # GPHS: 2
  - Power Output: 81 W_e (BOM
  - Dual opposing engines, each capable of delivering the design power in case one fails
  - 12 year design lifetime



»Stirling Engine design work was performed by the NASA Lewis Research Center in support of JPL

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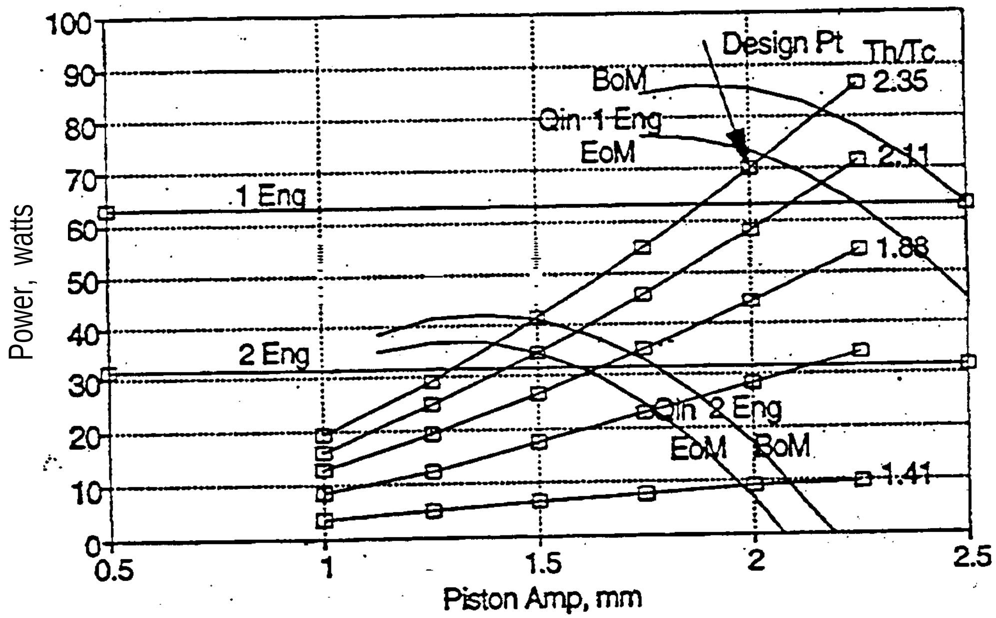
S ir ing Engine Design De ai s



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Stirling Engine Prospects

◆ Development Continues

- Space power development has tailed off
- Long-life space cryo-coolers are under development
  - » In-STEP Experiment (Hughes) to fly on Shuttle within the year
- Terrestrial uses still under development
  - » Automobiles
  - » Small power sources for remote sites

◆ Remaining Issues for Space Power System

- Two engine synchronization
- Vibration damping demonstration
- Failure modes demonstrations
- Lifetime